VU VRIJE UNIVERSITEIT AMSTERDAM

VU Research Portal

Effects of visual information and task constraints on intersegmental coordination in playground swinging

Post, A.A.; Peper, C.E.; Beek, P.J.

published in
Journal of Motor Behavior
2003

DOI (link to publisher)
10.1080/00222890309602122

document version
Publisher's PDF, also known as Version of record

Link to publication in VU Research Portal

citation for published version (APA)
Post, A. A., Peper, C. E., & Beek, P. J. (2003). Effects of visual information and task constraints on intersegmental coordination in playground swinging. *Journal of Motor Behavior*, *35*(1), 64-78. https://doi.org/10.1080/00222890309602122

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

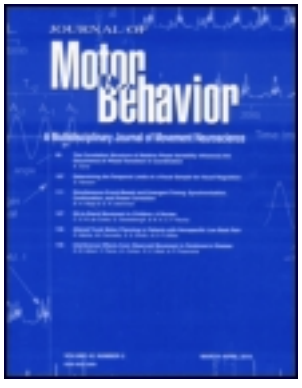
- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:
vuresearchportal.ub@vu.nl

Download date: 04. May. 2023

This article was downloaded by: [Vrije Universiteit Amsterdam]
On: 26 October 2012, At: 05:32
Publisher: Routledge
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of Motor Behavior
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/vjmb20

Effects of Visual Information and Task Constraints on Intersegmental Coordination in Playground Swinging

A. A. Post [a], C. E. Peper [a] & P. J. Beek [a]

[a] Institute for Fundamental and Clinical Human Movement Sciences Faculty of Human Movement Sciences, Vrije Universiteit, Amsterdam

Version of record first published: 01 Apr 2010.

To cite this article: A. A. Post, C. E. Peper & P. J. Beek (2003): Effects of Visual Information and Task Constraints on Intersegmental Coordination in Playground Swinging, Journal of Motor Behavior, 35:1, 64-78

To link to this article: http://dx.doi.org/10.1080/00222890309602122

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Journal of Motor Behavior, 2003, Vol. 35, No. 1, 64–78

Effects of Visual Information and Task Constraints on Intersegmental Coordination in Playground Swinging

A. A. Post
C. E. Peper
P. J. Beek
Institute for Fundamental and Clinical Human Movement Sciences
Faculty of Human Movement Sciences
Vrije Universiteit, Amsterdam

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

ABSTRACT. The authors investigated how and to what extent visual information and associated task constraints are negotiated in the coordinative structure of playground swinging. Participants ($N = 20$) were invited to pump a swing from rest to a prescribed maximal amplitude under 4 conditions: normal vision, no vision, and 2 visual conditions involving explicit phasing constraints. In the latter conditions, participants were presented with a flow pattern consisting of a periodically expanding and contracting optical structure. They were instructed to phase the swing motion so that the forward turning point coincided with either the maximal size (enhanced optical flow) or the minimal size (reduced optical flow) of the presented flow pattern. Removal of visual information clearly influenced the swinging behavior, in that intersegmental coordination became more stereotyped, reflecting a general stiffening of the swinger. The conditions involving explicit phasing requirements also affected the coordination, but in an opposite way: The coordination became less stereotyped. The two phasing instructions had differential effects: The intersegmental coordination deviated more from normal swinging (i.e., without phasing constraints) when optical flow was enhanced than when it was reduced. Collectively, those findings show that visual information plays a formative role in the coordinative structure of swinging, in that variations of visual information and task constraints were accompanied by subtle yet noticeable changes in intersegmental coordination.

Key words: coordination, playground swinging, task constraints, visual information

In everyday life, we move about with great ease. Our coordinated actions are usually delicately adapted to the task to be performed. While watching a baby bouncing in a baby bouncer (cf. Goldfield, Kay, & Warren, 1993), we realize that adaptation starts at a very young age. The production of coordinated movement calls for the harnessing of a vast number of degrees of freedom into a controllable system suitable for executing the task at hand. Such harnessing is achieved through nonrigid constraints or couplings between the functional components of the movement system, resulting in a synergy (Bernstein, 1967) or coordinative structure (Kugler, Kelso, & Turvey, 1980). A coordinative structure is a temporal arrangement of body components in two regards: First, it exists for a limited amount of time only, namely, as long as the activity persists; second, it specifies the temporal relations between those components in terms of their (relative) phasing. Although coordinative structures are often acquired in playful situations, the task itself might impose severe constraints on the behavior of the actor. A classic example of such a task is rhythmic movement around a single pivot point: playground swinging. That task is quite similar to the extensively investigated physical pendulum and can be studied in two dimensions with little loss of information, because all body segments are essentially confined to planar motion (Gore, 1970; Tea & Falk, 1968; Walker, 1989). To achieve successful energy insertion, actors need to adjust the movements of their body parts to the physical constraints of the swing. That requires sensitivity to the swing's mechanical properties, in particular its natural frequency. Given those severe mechanical constraints, it remains to be established whether, and to what extent, visual information and associated task constraints can be negotiated in the coordinative structure of playground swinging. We addressed that question in the present study.

Swinging Principles: Energy Mechanics

Recent inquiries into the action of pumping a swing into motion were of a theoretical nature (Case, 1996; Case & Swanson, 1990). In those studies, two methods of energy

Correspondence address: Lieke Peper, Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands. E-mail address: C_E_Peper@fbw.vu.nl

insertion, called *driven oscillation* and *parametric pumping*, were considered. In the driven oscillation method, the actor inserts energy into the swing by rotating the center of mass (CM) around the end of the swing's rope, whereas in the parametric pumping method, the actor inserts energy by raising and lowering the CM along the length of the rope. On the basis of algebraic analyses of a simple mechanical model of swinging in which the swinger was reduced to a point mass, Case and Swanson argued that at small amplitudes, swingers use the driven oscillation method rather than the parametric pumping method, which would be used only at large swinging amplitudes.

Recently, we experimentally verified the validity of those theoretical arguments (Post, 2001). To examine the contribution of the two just-described methods of energy insertion,[1] we distinguished two orthogonal directions in the planar movement of the CM, a radial direction (displacement along the rope, corresponding to parametric pumping) and a tangential direction (displacement perpendicular to the rope, aligned with the trajectory of the seat, roughly corresponding to driven oscillation). Given that we were interested in the method of energy insertion used by human swingers, participants were instructed to start from rest and to gradually pump the swing into motion in the course of a trial. The results showed that swingers moved their CM in both radial and tangential directions with respect to the swing's rotation axis (cf. Figure 1). It turned out that the relative contributions of those CM movements changed as the amplitude of swinging increased: Whereas at small amplitudes the tangential component dominated the CM movements, the relative contribution of the radial component increased with increasing amplitude; therefore, at large amplitudes, the radial component prevailed over the tangential component (Post, 2001). Anharmonicities in the displacement of the CM (examined by using θ, the angle between CM, hip, and rope; cf. Figure 1) were mainly caused by the irregularity of the radial component. By and large, those findings confirmed the validity of the analyses and corresponding arguments of Case (1996), albeit that the two distinguished methods of energy insertion proved to be more strongly blended than expected from a theoretical model in which the swinger is reduced to a point mass.

As anticipated, further analyses revealed that a swinger brings about the identified methods of energy insertion by coordinating movements of multiple body segments. Principal component analysis (PCA) allowed us to separate the coordinative structure for swinging from the swing mechanics (cf. Post, 2001). The first two PCA modes, which captured the large oscillatory movements of the swing, accounted for as much as 95% of the total variability in the swing–swinger system. The variability in the higher modes, representing the activity of the swinger, was concentrated mainly in the third and fourth modes (almost 5%). Those two modes could be associated with the simultaneous clockwise and anticlockwise rotations of the trunk and the lower legs. We examined temporal relations by means of cross-correlations between the tangential movements of the CM and the swing motion, between the radial movements of the CM and the swing motion, and between the trunk and the lower leg movements. High correlations were observed in all paired combinations. Those correlations occurred at stable phase lags that, collectively, characterized the coordinative structure for optimal energy insertion.

Research Questions

A hallmark property of coordinative structures is that their formative constraints are based on information rather than on rigid, mechanical linkages; that is, they are "softly assembled" (cf. Kugler & Turvey, 1987). Because coordinative structures must be attuned to the prevailing task, the pickup of task-specific information is necessary for their assembly and preservation. Several perceptual systems are involved in playground swinging (most notably the vestibular, the proprioceptive, and the visual systems). Given that the coordinative structure of swinging is largely dictated by the mechanics of the swing's motion, it is an open question how and to what extent that structure can adapt to changes in the available perceptual (e.g., visual) information and associated task constraints. We conducted the present experiment to resolve that issue. In particular, three research questions were addressed.

The first research question was simply: Does removal of visual information result in changes in intersegmental coordination? If visual information were used in the assembly and preservation of the coordinative structure of swinging, then one would expect the coordination to become more stereotyped when such information is not available, because, in that case, tuning to the visual environment is impossible. To examine that prediction, one needs an adequate characterization of the coordinative structure, which one can obtain by applying PCA and cross-correlation analysis (see Method section). PCA is an unbiased method for searching for patterns in multivariate data sets by determining the existence and relative importance of the covariances between the obtained time series; subsequently, one can analyze those covariances in more detail by using cross-correlations. Because the PCA modes are ordered according to the percentage of variance explained (see Method section), the first modes are the most important descriptors of the observed pattern. Post (2001) demonstrated that, in unconstrained swinging, the first four PCA modes accounted for more than 99% of the variance. Because 95% of the total variance could be attributed to the passive movements of the swing (PCA Modes 1 and 2), only 5% of the variance was associated with the activity of the swinger. The swinger's activity was dominated by synchronous isodirectional trunk–leg rotations (Modes 3 and 4, which accounted for 97% of the remaining 5% of the variance). On the basis of those results, the expectation that blindfolded swinging will result in more stereotyped movements can be operationalized in terms of a predicted increase in the importance of the first four PCA modes relative to that of the higher (less important) modes, because the latter are interpreted as reflecting active modulations of the intersegmental coordi-

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

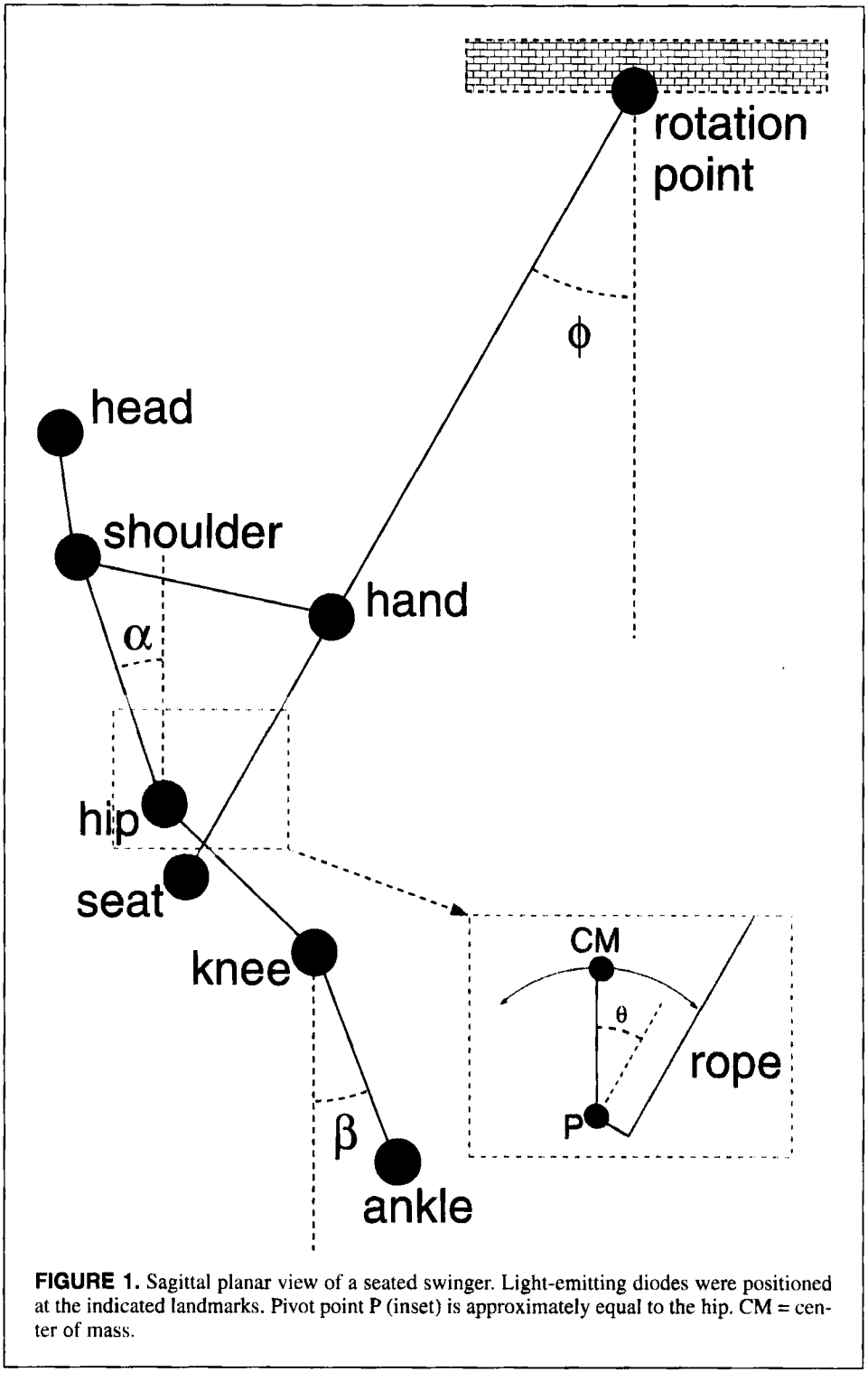


FIGURE 1. Sagittal planar view of a seated swinger. Light-emitting diodes were positioned at the indicated landmarks. Pivot point P (inset) is approximately equal to the hip. CM = center of mass.

nation pattern. Given that the third and fourth PCA modes are related to trunk–leg movements, one would expect the correlation between trunk and leg movements to be stronger as well. The possible consequences of changes in the coordinative structure for energy insertion (CM mechanics) were also evaluated.

The second research question was the following: Does the introduction of visual conditions involving explicit phasing constraints with regard to the visual environment lead to changes in intersegmental coordination? In particular, by inviting the swinger to phase his or her swinging movements in accordance with an oscillating visual display, one introduces an additional task constraint that might or might not affect the intersegmental coordination. On the one hand, because playground swinging is a highly constrained task, one might argue that there will be little room left for adapta-

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

tion to yet another constraint. On the other hand, however, one might argue that the information-based character of coordinative structures is an inalienable property and that therefore changes in the informational constraints will always result in changes in coordination. In previous research, Post, Daffertshofer, and Beek (2000) showed that in juggling, adding a task constraint (in the form of a frequency instruction) resulted in an increase in the dimensionality of the coordination dynamics. If that finding is generalizable, then one might expect that the introduction of additional phasing constraints will also lead to an increase in the dimensionality of coordination in swinging (i.e., higher PCA modes will become more important), reflecting the changes in the coordinative structure. Furthermore, the mechanics of swinging leads to specific expectations regarding the manner of adaptation to the additional phasing constraints. We required the swinger to gradually increase the swinging amplitude from zero to a prescribed maximal value in the course of a trial, because pumping a swing from a standstill requires the swinger to use a specific kind of coordinative activity to ensure that much more energy is inserted into the swing than is lost because of damping and friction. Although, once in motion, the movements of the swinger are largely governed by the oscillation of the swing, there is still room for modulation, especially at small amplitudes: Activity of the swinger at a frequency slightly lower (higher) than the natural frequency of the compound system can result in a gradually increasing phase lag (lead). At large amplitudes, however, the energy inserted by the swinger is small in comparison with the total energy contained in the swing–swinger system. As such, the resulting frequency modulation is marginal, rendering the phase adaptation rather ineffective. Because the phase adaptation process coincides with amplitude increase over the trial, one would expect that the window of phase change available to the swinger would be largely restricted to the first portion of a trial.

The third research question was: What properties of the available visual information, if any, are being used in modulating the intersegmental coordination? Clearly, swinging results in an oscillatory flow field, involving rhythmic expansion and contraction of the visual scene. The influence of oscillating optical flow fields has been examined rather extensively in the context of postural control. In that context, a rhythmic optical expansion–contraction pattern has been found to induce enhanced postural sway, phase-locked in such a way that the visually perceived oscillations are reduced (e.g., Dijkstra, Schöner, Giese, & Gielen, 1994). Thus, visual information appears to be used so that a relatively stationary relation with the visual environment can be attained. In playground swinging, the situation is rather different, because task performance itself results in an oscillating flow field. For a stationary visual environment, the amplitude of those oscillations specifies the amplitude of the swinging movement. One might therefore expect the presentation of an oscillating visual scene to have several effects. (A) If the optical flow field is used irrespectively of other sources of information (e.g., vestibular and proprioceptive), enlargement of the visually perceived amplitude might lead to a reduction in the amplitude of swinging because the oscillations seem larger than they actually are. The modulations of amplitude would then be expected to scale with the amplitude of the visual oscillations. (B) If additional perceptual information about self-motion is used in combination with the visual information, the imposed optical flow field will result in an incongruity with regard to the amplitude of actual self-motion and the visually perceived self-motion. In view of the results of Dijkstra et al. (1994), one might expect that participants would favor a coupling with the visual environment in which that incongruity is minimal, that is, in which the magnitude of the oscillating optical flow is closest to the one observed when swinging in a stationary visual environment. One would therefore expect that swinging in the direction opposite to that of visually perceived self-motion, which reduces the optical flow (cf. Figure 2B), would be preferred over swinging in the same direction, which enhances the optical flow (cf. Figure 2A). (C) In contrast, if perception of the direction of self-motion is essential in the coordination of swinging, one would expect that movement in the same direction as the optically specified direction of self-motion (cf. Figure 2A) would be preferred over movement in the opposite direction (cf. Figure 2B), because the latter situation entails a mismatch between the visually perceived direction of motion and the actual direction of motion.

To examine the second and third research questions, we instructed participants to coordinate their swinging movements with the visual display of a rhythmically expanding and contracting rectangle. We assessed the effects of that additional task constraint on intersegmental coordination by comparing it with unconstrained swinging. Furthermore, by asking the participants to coordinate their forward (backward) movements with either the expansion (contraction) phase (resulting in optical flow enhancement, OFE; cf. Figure 2A) or the contraction (expansion) phase (resulting in optical flow reduction, OFR; cf. Figure 2B), we evaluated the three alternative expectations outlined for the third question. That evaluation involved analyses of swinging amplitude (Expectation A, i.e., larger amplitude for OFR than for OFE) and of the intersegmental coordination itself, using smoothness and dimensionality measures (Expectations B and C, i.e., smoother and more effective behavior for either OFR or OFE, respectively).

Method

Participants

Eleven men and 9 women (mean age = 29.4 years, *SD* = 6.6 years) who were affiliated with the Faculty of Human Movement Sciences as students or staff members participated in the experiment on a voluntary basis after having signed an informed-consent statement. Each of them reported normal or corrected-to-normal vision and no history of vestibular or balance problems. In order to use anatomical regression

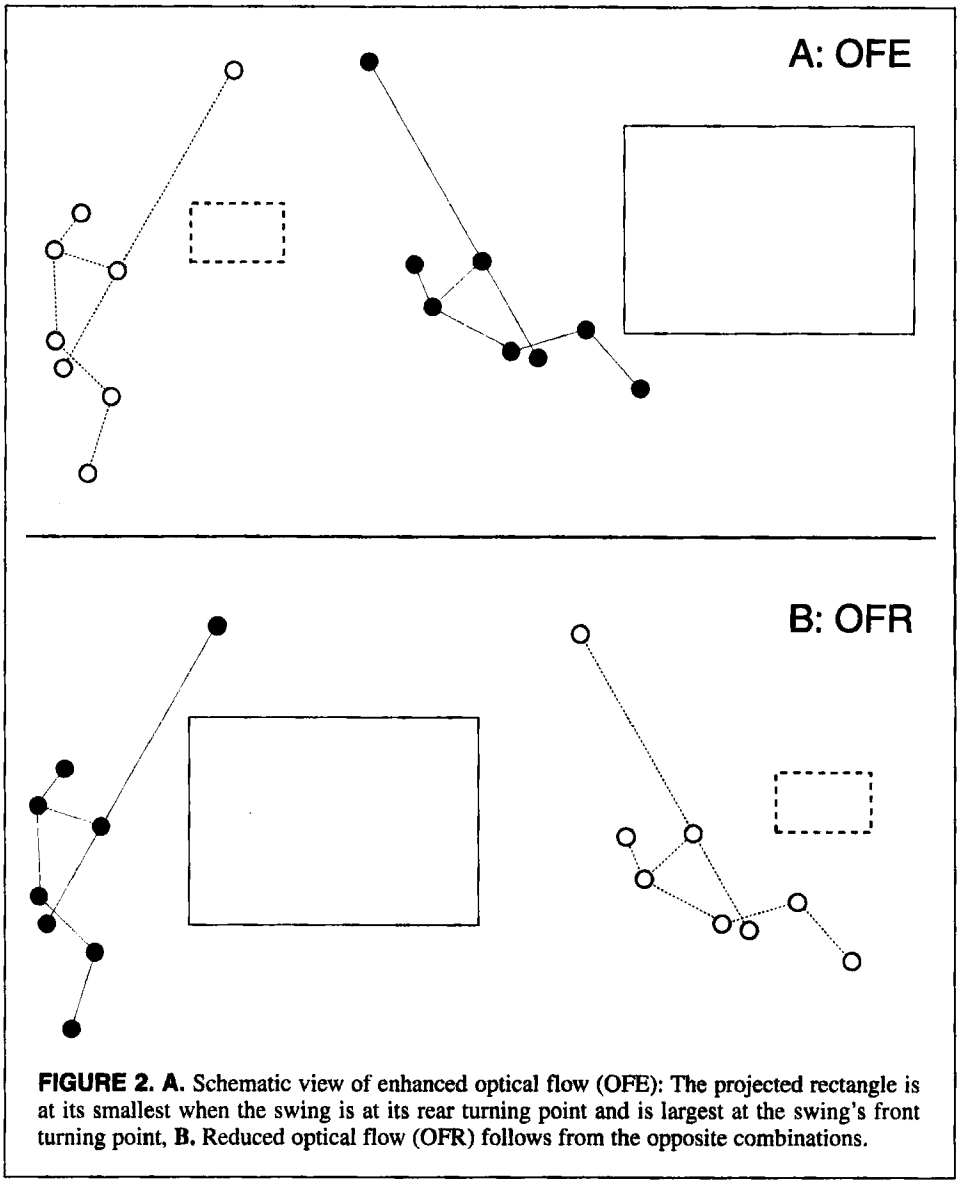


FIGURE 2. A. Schematic view of enhanced optical flow (OFE): The projected rectangle is at its smallest when the swing is at its rear turning point and is largest at the swing's front turning point, **B.** Reduced optical flow (OFR) follows from the opposite combinations.

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

equations (Plagenhoef, Evans, & Abdelnour, 1983), we measured the height and the weight of each participant.

Experimental Setup

The movements of the participants were measured while they swung on a playground swing (RESPO Model 8000; Vroomshoop, The Netherlands). The distance between the floor and the center of the swing's rotation axis was 2.58 m, the length of the suspension chains 1.75 m, and the dimensions of the seat 0.44 m × 0.22 m. A position and a velocity sensor were attached to the rotation axis of the swing, and a force transducer was integrated into one of the suspension chains just below the rotation axis. Participants could not reach the ground with their feet. A horizontal bar hanging just below the ceiling at a height of 2.70 m indicated the maximal swinging amplitude of 70°. To manipulate the optical flow field, we placed a flat rear projection screen (width 1.39 m, height 1.05 m) in front of the swing, the bottom edge 1.54 m above the floor, at a distance of 3.66 m from the swing at rest. The environment around the projection screen was covered with black cloth. In addition, the windows of the lab were completely covered with blackout screens; light leakage at the entrance door was excluded with black cloth.

The presentation of the experimental conditions and data collection were controlled with a PC. We used a second PC (Amiga 3000) to generate the display and to project it on the screen with a video projector (Panasonic PT 102N) with a 50-Hz refresh rate. The display consisted of a blue (for minimal luminance) rectangle on a black background. Changing the size of that rectangle generated an optical expansion and contraction pattern. The image resolution was 600 × 200 (horizontal × vertical) pixels, resulting in a rectangle with maximal dimensions of 0.88 m × 0.55 m and minimal dimensions of 0.11 m × 0.07 m. When swinging at an amplitude of 70°, the corresponding visual angles in the OFE condition were 16.5° × 10.3° at the turning point clos-

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

est to the screen (front) and 1.5° × 0.9° at the turning point farthest from the screen (back); in the OFR condition, those values were 2.0° × 1.3° (front) and 11.7° × 7.3° (back). The angles of the static display of intermediate size (0.55 m × 0.32 m), used in the baseline condition, were 10.3° × 6.0° (front) and 7.3° × 4.3° (back). The oscillating expansion–contraction patterns were based on a computer-generated sinusoid that oscillated at the participant's preferred swinging frequency, as determined during the baseline condition (see the following). The sinusoid data were sent to the Amiga, which generated the required display at that swinging frequency, independently of the swinger's actual movements. Thus, frequency locking was ensured, but the required phasing was left open to the swinger.

Infrared-light-emitting diodes (LEDs) were placed on salient landmarks on the participant's body (see the following) and were recorded with a three-dimensional (3D) movement registration system (Northern Digital, Waterloo, Ont; Optotrak system 3020) consisting of one control unit and two sensor beams carrying three position sensors each. The sensor beams were placed at the right-hand side of the participant (who was seated on the swing) at such distances and angles that all LEDs were visible throughout almost the entire range of the swinging movement (momentary occlusion of the LEDs by the support frame of the swing was unavoidable). LEDs were attached with adhesive tape to the right-hand side of the swing (seat and rotation point) and to the right side of the participant's body (head, just above the ear; shoulder; hand at the distal part of the third metacarpal; hip at the level of the trochanter major; knee at the lateral epicondyle of the femur; and ankle at the lateral malleolus; cf. Figure 1). The position of each LED was recorded in 3D real-world coordinates. Experimental data were collected at a sampling rate of 150 Hz.

The position data recorded by the Optotrak system were interpolated linearly when small gaps caused by occlusion were present (maximal gap size was 10 samples). Those data were filtered with a second-order bidirectional Butterworth filter (cutoff frequency 5.0 Hz for the x component and 10.0 Hz for the y component of the position data). The data of 2 participants were excluded from further analysis. The reasons for exclusion were equipment failure during the experiment and inability to meet the gradual amplitude increase requirement (see the following), respectively.

Procedure

The participants were instructed to pump the swing from rest into motion and to increase the swing's amplitude in a regular manner to the indicated maximum of about 70° without pushing against the ground with their feet and while looking at the screen at all times. They were told to avoid making contact with the ceiling and to perform the upswing movements as smoothly and as regularly as possible throughout the trial. Given that the maximal amplitude could well be reached within the duration of a trial, participants were further instructed not to start too vigorously, which would necessitate their skipping a cycle later on, but to spread the pumping activity evenly over the entire trial. Each participant was allowed maximally three 10-s practice trials in the baseline condition (see the following) as well as in the OFR and OFE conditions. When the experimenter judged the participant to be capable of swinging in the required manner, the experiment proper began.

The experiment started with five trials in the baseline condition (swinging in the dark, with a stationary display of intermediate size projected on the screen). Our purpose in using that baseline condition was not only to reduce learning effects but also to estimate the preferred frequency, which was later used as the oscillation frequency of the visual scene in the OFR and OFE conditions. That procedure ensured that a stable phase relation with the oscillating display could be maintained throughout the trial.

Subsequently, the four experimental conditions were presented to each participant: normal vision (NV; full ambient optical array, no display projected on the screen), blindfolded (BF; no visual information), OFE (moving in the forward direction while the square diverged and backward while the square converged; cf. Figure 2A), and OFR (moving in the forward direction while the square converged and backward while the square diverged; cf. Figure 2B). When the latter two conditions were performed, the room was completely darkened, and, to avoid any adaptation to the darkness, we briefly switched on a stage light (1,000 W) between the trials. Each condition was presented five times. All trials (including the baseline trials) lasted 30 s. After each block of five trials, the participants were informed about the next condition. The order of the condition blocks was randomized over participants. The experiment lasted approximately 1 hr per participant.

Data Reduction and Analysis

The maximal amplitude of the swing (ϕ_{max}) was calculated as the difference between the maximal positive and negative excursions divided by two. In that way we could assess whether the participants had complied with the requirement of pumping the swing to the indicated maximum.

CM mechanics. We calculated the position of body segments and their individual CMs from the position of the body markers by using anatomical regression equations (Plagenhoef et al., 1983). Summation of those individual CMs resulted in a time series of the aggregate CM in Cartesian coordinates, which we used to determine the distance between the CM and its projection on the rope in both the radial and the tangential directions. An example of the CM trajectory during a trial is depicted in Figure 3. We used a peak-finding algorithm to calculate the amplitude, (positive peak – negative peak)/2, for each individual cycle in those signals. Thus, both A_{tan} (amplitude in tangential direction) and A_{rad} (amplitude in radial direction) were obtained. We determined the amplitude dynamics over the course of a trial by using the mean first derivative of A_{tan} and A_{rad}, that is, V_{tan} and V_{rad}.

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

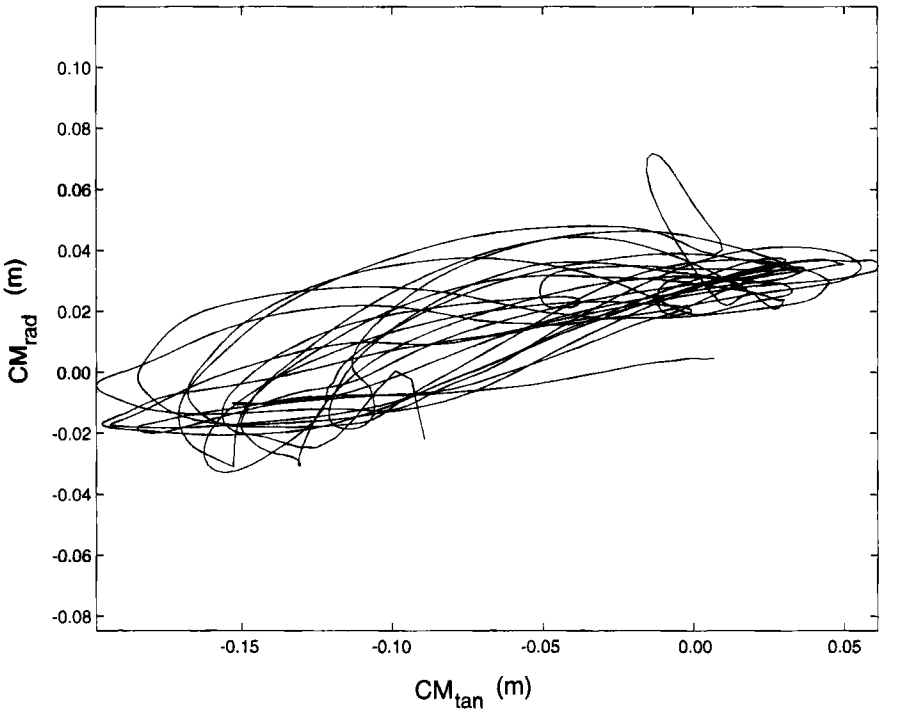


FIGURE 3. Representative example of the trajectory of the center of mass in both the radial (CM_{rad}) and tangential (CM_{tan}) directions during a trial.

Harmonicity of the angle θ (cf. Figure 1), referred to as $H(\theta)$, was used as a measure of the regularity of the time evolution of that angle. That measure of harmonicity, which was inspired by the method developed by Peper, Beek, and van Wieringen (1995), indicates the smoothness of the rotation of the CM. We estimated $H(\theta)$ by Fourier-transforming the data and comparing the spectral power of the main frequency ω_0 (± a bandwidth of 10% around that frequency) with the sum of the nine subsequent higher harmonics (each with the same bandwidth), using the following equation:

$$H(\theta) = 1 - \frac{\sum p_{\omega_i}}{p_{\omega_0}}. \quad (1)$$

A value $H(\theta) = 1$ means a perfectly harmonic sinusoid; values smaller than 1 indicate an increasing influence of higher harmonics.

Principal components. The relevance of PCA for the analysis of human movement is illustrated by its application in a number of recent studies focusing on a variety of motor behaviors, including stance (Alexandrov, Frolov, & Massion, 1998; Vernazza-Martin, Martin, & Massion, 1999), walking (Mah, Hulliger, Lee, & O'Callaghan, 1994), reaching (Jaric, Ferreira, Tortoza, Marconi, & Almeida, 1999; Pigeon, Yahia, Mitnitski, & Feldman, 2000), pedalo riding (Haken, 1996), and juggling (Post et al., 2000). Post (2001) established the suitability of PCA for the analysis of the present task, playground swinging. In view of the numerous publications that have recently appeared about the PCA technique, we confine ourselves to a brief, nontechnical introduction.

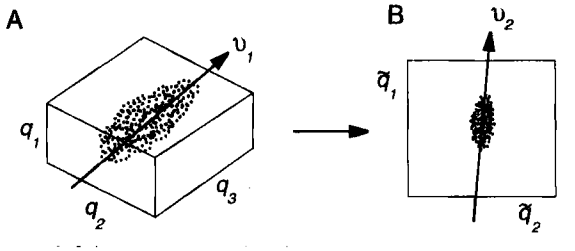


FIGURE 4. Representation of principal component analysis in three dimensions (**A**), and subsequently after projection in two dimensions (**B**). q = signal, υ = eigenvector, and $\tilde{q}$ = signal after projection.

With PCA, the measured time series (e.g., q_1, q_2, and q_3) are combined to form a signal q that exists in a multidimensional space (in the example, three-dimensional). In that space, the vector that points in the direction of maximal variability of the signal (cf. Figure 4A) is sought; that vector is the first eigenvector (υ_1). The length of that vector corresponds to its relative importance to the pattern as a whole and is called the first eigenvalue. The first mode is thus defined. Subsequently, the space is reduced with one dimension through projection, with the restriction that the new space projection be orthogonal to υ_1 (cf. Figure 4B). A

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

new vector υ_2 is sought in that new space in the same manner as for υ_1. That procedure is repeated until all dimensions have been used. Thus, the original system is linearly transformed into a new orthogonal coordinate system in which the variables on the axes have an increasingly reduced importance for the system. The original data set can be finally projected onto every single eigenvector, leading to $\xi_k(t) = \upsilon_k q(t)$: the temporal evolution of the original system in the new coordinate space. When properly selected, projections $\xi_k(t)$ might result in useful visualization of synergies in the behavior of the participant. All (x, y) time series (N = 16) obtained with the Optotrak measurements were used as input for the PCA calculations. That procedure was applied to each trial individually.

Cross-correlations. We applied cross-correlation analysis in the same manner as in Post (2001), namely, to the time series of the tangential movement of the CM and the swing rotation angle $\rho(CM_{tan},\phi)$, the radial movement of the CM and the swing rotation angle $\rho(CM_{rad},\phi)$, and the rotation angles of trunk and lower leg $\rho(\alpha,\beta)$ in order to establish their degree of coupling. In so doing, insight was gained into the changes in the underlying coordination patterns of swinging as a function of the experimental conditions. For all combinations, the correlation values ρ were calculated at different time lags τ. The optimal value of ρ and the associated time lag τ were used. The time lag was converted into a phase difference (in degrees) between the two time series entered in the cross-correlation, calculated as the time lag τ divided by the cycle period (the inverse of ω_0) times 360°.

Relative phase variability. To investigate the predictions concerning OFE and OFR swinging, we determined estimates of continuous relative phase φ between the time series of the swing and the stimulus within each trial at a rate of 150 Hz. Continuous relative phase was defined, for each sample, as the difference between the phases of the swing and the projected rectangle ($\varphi = \varphi_{swing} - \varphi_{rectangle}$), which were calculated as

$$\varphi_i = \arctan(\phi_i / \dot{\phi}_i), \tag{2}$$

where $i \in$ {swing, rectangle}. Positive values of φ indicated that the motion of the swing lagged behind the motion of the presented optical field. Mean values of φ were calculated across identical trials within each experimental condition. We determined the variability of φ within trials by using circular statistics. The dispersion of relative phase (uniformity) was calculated following Mardia (1972):

$$r = \frac{\sqrt{\left(\sum \cos\varphi\right)^2 + \left(\sum \sin\varphi\right)^2}}{N}, \tag{3}$$

where N is the number of samples in the time series. The uniformity (r) is restricted to the interval [0,1]. By transforming it to the range of 0 to ∞, using

$$s_0 = (-2 \ln r)^{1/2}, \tag{4}$$

one obtains the "transformed circular variance" (s_0), which is comparable to the ordinary standard deviation (with low values indicating low variability) and which permits the use of tests based on standard normal theory (Mardia, 1972).

Statistics

For all dependent variables, the focus in the analyses was on three comparisons pertaining to (a) the effect of visual information (BF versus NV); (b) the effects of the added task constraints (AC; prescribed coordination with visual display [i.e., OFE and OFR aggregated = AC] versus no prescription [i.e., NV]); and (c) the effect of the required coupling to the optical flow field (i.e., OFR versus OFE). We achieved those comparisons by using paired-samples t tests. Because the number of t tests remained small enough to allow us to refrain from using critical value adjustments (Keppel, 1991), we performed all tests with the conventional significance level of $p < .05$. We transformed the PCA and cross-correlation values into Fisher's z values before averaging them over identical trials and testing them statistically (the reported averaged values were inversely transformed).

Results

General Remarks

Before presenting the results according to the expectations formulated in the introduction, we briefly summarize the main results of the individual analyses performed to give a first impression of the performance in the various conditions. Group-averaged values of all variables for each condition are collected in Table 1. All participants were able to pump the swing to an amplitude close to the indicated maximum of 70°: The average value of ϕ_{max} was 62.2° (SD = 6.5°). The preferred frequency (as calculated on the basis of the baseline trials for each participant individually) was nearly the same for all participants: 0.384 Hz (SD = 0.004 Hz). As anticipated, the swinging frequency remained unaffected by the experimental manipulations.

CM Mechanics

The variables pertaining to (the changes in) the location of the CM relative to the swing rope (averaged over conditions) all differed significantly from zero. The nonzero values of A_{tan} and A_{rad} imply that the radial as well as the tangential directions contributed to the increase of the swinging amplitude. The fact that the values of V_{tan} and V_{rad} also differed from zero indicates that those contributions were not stationary but changed in the course of a trial (A_{tan} reduced and A_{rad} increased). We examined the coupling between the CM movement and the swing mechanics by calculating the cross-correlations between the tangential movement of the CM and the excursion angle of the swing $\rho(CM_{tan},\phi)$, and between the radial movement of the CM and the excursion angle of the swing $\rho(CM_{rad},\phi)$. The obtained cross-correlation values suggested that stable phase relations were present between those variables in all conditions. The time lag values $\tau(CM_{tan},\phi)$ and $\tau(CM_{rad},\phi)$ showed that the swing rotation systematically lagged behind the CM movements.

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

TABLE 1
Mean Values of the Test Variables, Averaged Over Identical Trials and Participants

Variable	Visual condition		Task constraints		Phasing mode	
	BF	NV	AC	NV	OFR	OFE
ϕ_{max} (°)	62.4	65.2	60.7	65.2	60.3	61.0
A_{rad} (m)	0.0183	0.0164	0.0139	0.0164	0.0147	0.0131
V_{rad} (m/s)	0.0010	0.0005	0.0006	0.0005	0.0004	0.0008
A_{tan} (m)	0.0878	0.0836	0.0808	0.0836	0.0802	0.0814
V_{tan} (m/s)	–0.0019	–0.0026	–0.0016	–0.0026	–0.0021	–0.0010
$H(\theta)$(–)	0.9693	0.9686	0.9635	0.9686	0.9664	0.9603
$\rho(CM_{tan},\phi)$ (–)	0.762	0.736	0.748	0.736	0.745	0.750
$\tau(CM_{tan},\phi)$ (°)	101.77	104.40	106.35	104.40	103.21	109.50
$\rho(CM_{rad},\phi)$ (–)	0.716	0.677	0.672	0.677	0.665	0.678
$\tau(CM_{rad},\phi)$ (°)	127.04	132.93	127.26	132.93	125.79	128.74
PCA12 (%)	94.89	95.18	95.13	95.18	95.16	95.10
PCA34 (%)[a]	97.34	96.91	96.65	96.91	96.60	96.71
PCA56 (%)[a]	2.04	2.34	2.72	2.34	2.78	2.67
$\rho(\alpha,\beta)$ (–)	0.961	0.956	0.951	0.956	0.953	0.947
$\tau(\alpha,\beta)$ (°)	14.92	15.98	17.40	15.98	15.68	19.12
$s_0(\phi)$(–)					0.1980	0.1836

Note. BF = blindfolded, no visual information; NV = normal vision; AC = added task constraint; OFR = optical flow reduction; and OFE = optical flow enhancement. The rows (variables; see text for definitions) are divided into four segments: In the first, task mechanics are addressed; the second pertains to coupling between swinger and mechanics; the third refers to interlimb coupling; and the fourth concerns the coupling between perception and action. In the columns are the three sets of paired *t* tests corresponding to the three research questions addressed in the present study. Dash (–) indicates a dimensionless variable.
[a]Percentage of the decompressed activity of the swinger (see text for details).

Interlimb Coordination

In general, the PCA produced results similar to those reported by Post (2001). Irrespective of experimental manipulations, a small number of modes accounted for nearly all the variance in the system: Of the 16 available modes, the first 4 accounted for 99% of the variance. That finding implies that the dimensionality of the system was strongly reduced: For an adequate description of that 16-dimensional system, only 4 dimensions are needed. After we projected the original data on the newly found coordinate system, we found that the first 2 modes (PCA12) coincided with the large passive motion of the swing (i.e., the swing oscillating in the *x* and *y* directions; see Figure 5A). The fact that those 2 modes accounted for approximately 95% of the total variance indicated that the motion of the swinger was largely determined by the mechanics of the swing. By removing those first 2 modes and rescaling the sum of all the remaining modes to 100%, we could examine those modes more closely in a "decompressed" fashion. As became apparent from the projections, the remaining modes represented the (active) movements of the swinger. The first 2 modes of that reduced set (PCA34) were associated with synchronous isodirectional trunk–leg rotations (see Figure 5B) and accounted for as much as 97% of the swinger's activity. The subsequent 2 modes (PCA56) captured additional movements of the swinger (either along the rope of the swing or trunk–leg rotations with a phasing relation opposite to PCA34) representing 2.5% of the activity. Because only less than 1% of the (decompressed) activity remained to be accounted for, the contribution of Modes 7–16 was negligibly small.

We determined the degree of interlimb coupling by using the cross-correlation between the trunk angle α and the lower leg angle β. Figure 6 depicts representative examples of the evolution of α and β as obtained for two trials (OFE and OFR conditions). Cross-correlations $\rho(\alpha,\beta)$ collapsed over identical trials and participants are presented in Table 1. The high values in all conditions (almost equal to 1) indicated that α and β were strongly coupled. One might therefore conclude that the two segments are not controlled independently but form an integral part of the coordinative structure for swinging. The angular rotation of the trunk lagged slightly behind the angular rotation of the lower leg (cf. $\tau[\alpha,\beta]$ in Table 1).

Perception–Action Coupling

Close inspection of a representative time series of the continuous relative phase φ (cf. Figure 7A and B) showed that

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

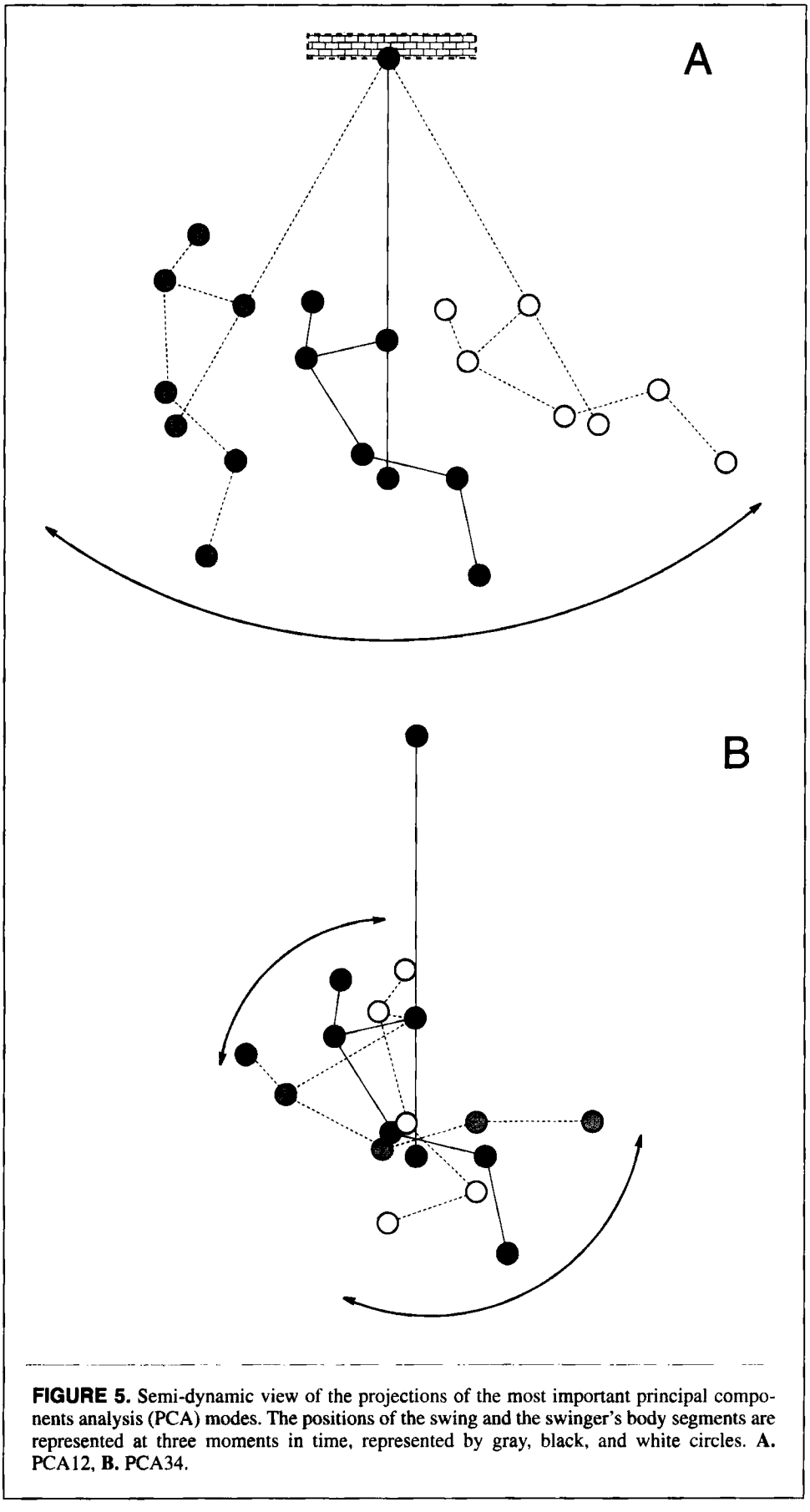


FIGURE 5. Semi-dynamic view of the projections of the most important principal components analysis (PCA) modes. The positions of the swing and the swinger's body segments are represented at three moments in time, represented by gray, black, and white circles. **A.** PCA12, **B.** PCA34.

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

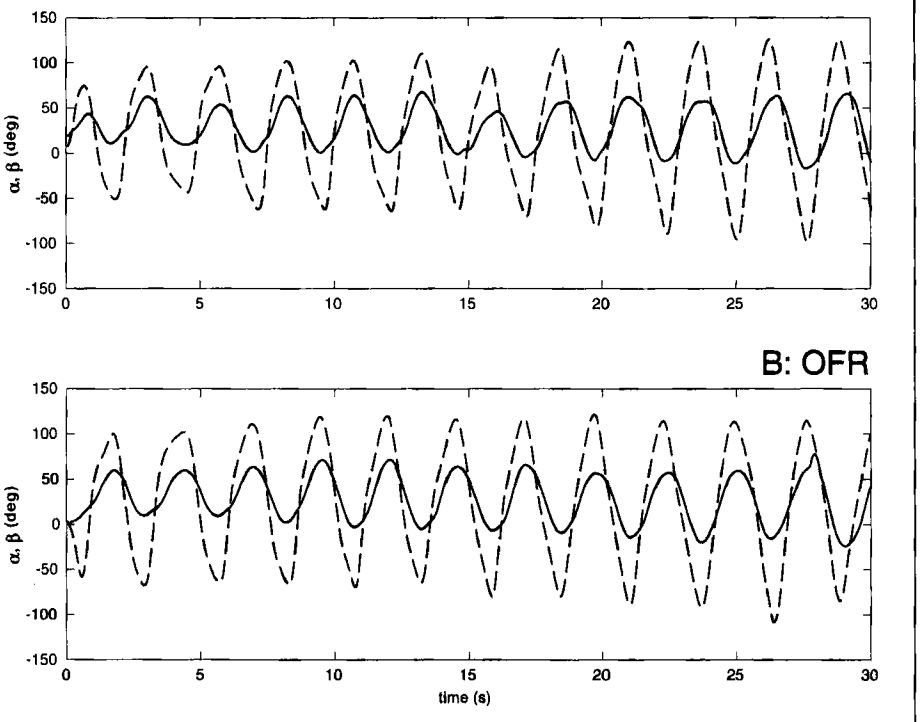


FIGURE 6. Typical evolution of α (solid) and β (dashed) as a function of time. **A.** OFE (enhanced optical flow) condition, **B.** OFR (reduced optical flow) condition.

φ was characterized by an initial relaxation toward the required relative phase that subsequently evolved smoothly into an increasing phase difference near the end of the trial. The latter pattern of change was caused by a frequency deviation between the (harmonically evolving) oscillation of the optical flow field and the (decreasingly harmonic) swing oscillation at large amplitudes. In response to that nonstationarity, we high-pass filtered (fourth-order bidirectional Butterworth filter, cutoff frequency 0.7 Hz) the time series of continuous relative phase in order to extract the fluctuations around that slowly evolving process (cf. Figure 7C and D). In Table 1, scores of s_0 (circular variability of φ) averaged across identical trials and participants are presented. Figures 7A and B corroborate the prediction, formulated in the introduction (cf. the second research question), that swingers adjust their phase mainly within the first part of a trial (i.e., within the first 10 s, corresponding to an amplitude of about 20°). The unwanted slight deviation from the intended phase near the end of the trial underscores the fact that phase adjustment is possible only at small amplitudes.

Effects of the Removal of Visual Information

PCA12 accounted for significantly less variance in the BF condition (94.89%) than in the NV condition (95.18%), $t(17) = -2.939$, $p < .01$, whereas PCA34 accounted for significantly more (decompressed) variance in the BF condition (97.34%) than in the NV condition (96.91%), $t(17) = 3.715$, $p < .005$. The simultaneous decrease of PCA12 and increase of PCA34 in the BF condition was accompanied by a significant decrease of PCA56: 2.04% in the BF condition versus 2.34% in the NV condition, $t(17) = -2.884$, $p < .01$. That finding implies that the swinging activity became more rigid and stereotyped in the absence of visual information. Trunk–leg coupling ρ(α,β) was significantly higher in the BF condition (.961) than in the NV condition (.956), $t(17) = 3.070$, $p < .01$. That result accords with the results for PCA34, which corroborates the interpretation of those modes as representing the trunk–lower leg synergy (see Post, 2001). The difference in phasing between trunk and leg tended toward significance (14.92° in the BF condition, 15.98° in the NV condition), $t(17) = -2.008$, $p = .061$. On the assumption that the NV condition defines optimal swinging behavior, that finding might indicate that, without vision, a swinger is less successful in inserting energy into the swing's motion.

Nearly all variables related to the swing mechanics were affected by the removal of visual information. Regarding the cross-correlations pertaining to the relation between the CM and the swing motion, $\rho(CM_{tan},\phi)$ was significantly higher in the BF condition (.762) than in the NV condition (.736), $t(17) = 3.135$, $p < .01$; $\rho(CM_{rad},\phi)$ was also significantly higher in the BF condition (.716) than in the NV condition (.677), $t(17) = 3.993$, $p < .005$. The phasing of the latter coupling was also affected: $\tau(CM_{rad},\phi)$ was less phase advanced in the BF condition (127.0°) than in the NV condition (132.9°), $t(17) = -2.258$, $p < .05$. The maximal swing ampli-

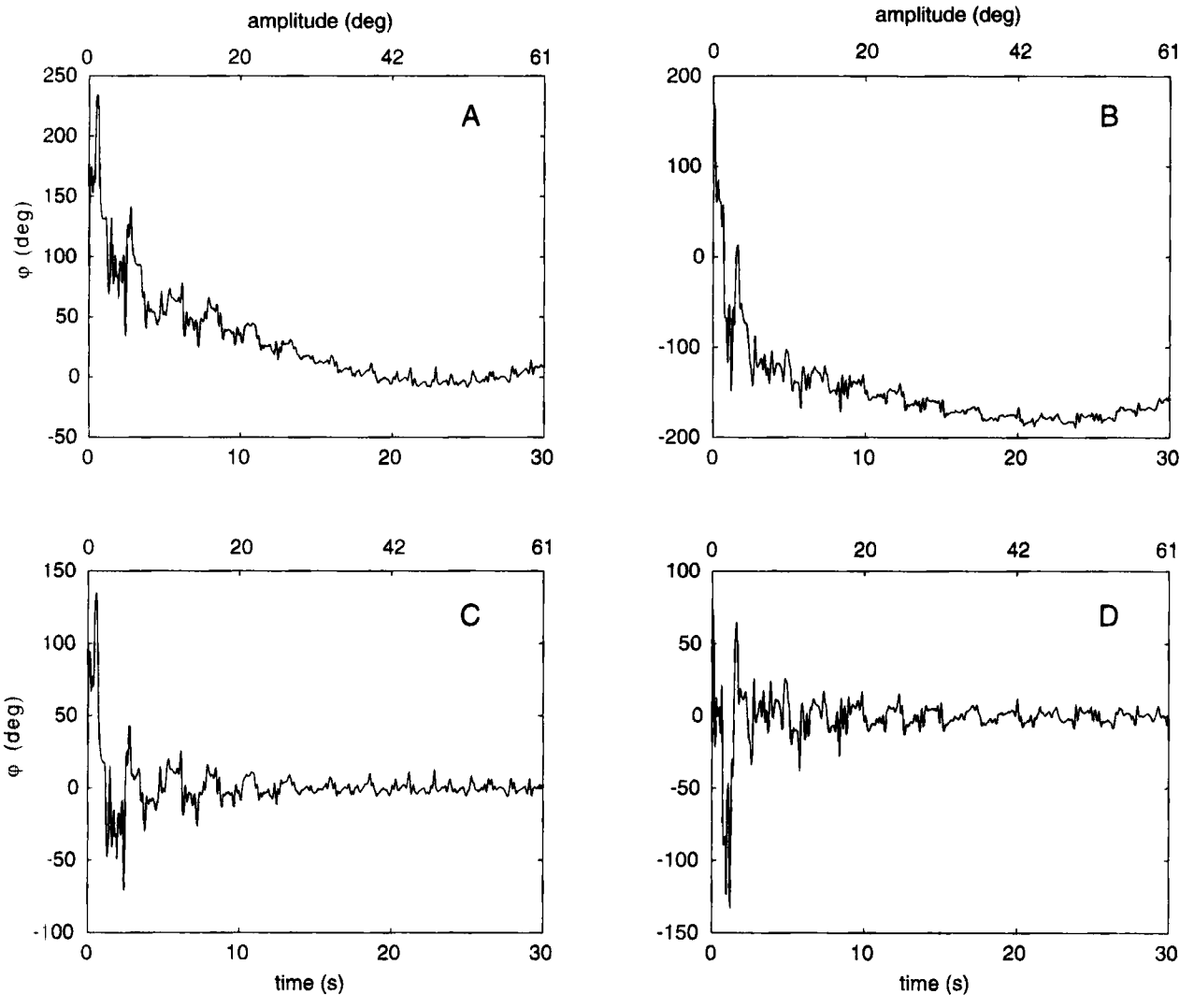


FIGURE 7. Continuous relative phase (φ) as a function of time (bottom axis) as well as amplitude (top axis), as obtained for two representative trials in the enhanced optical flow (OFE; **A** and **C**) and reduced optical flow (OFR; **B** and **D**) conditions. The same trials are presented in C and D as in A and B, respectively, after high-pass filtering.

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

tudes (ϕ_{max}) were significantly smaller in the BF condition than in the NV condition (62.4° and 65.2°, respectively), $t(17) = -4.358$, $p < .0005$. A_{rad} was significantly affected by the removal of visual information: On average, it was larger in the BF condition (0.0183 m) than in the NV condition (0.0164 m), $t(17) = 2.396$, $p < .05$. The values of V_{rad} obtained in the BF condition (0.0010 m/s) were significantly larger than those obtained in the NV condition (0.0005 m/s), $t(17) = 2.980$, $p < .01$, indicating that there was a more rapid increase in the radial amplitude of the CM. A_{tan} was affected in the same fashion as A_{rad}: On average, it was larger in the BF condition (0.0878 m) than in the NV condition (0.0836 m), $t(17) = 2.401$, $p < .05$. The significant effect on V_{tan} implied that the tangential amplitude decreased more slowly in the BF condition (–0.0019 m/s) than in the NV condition (–0.0026 m/s), $t(17) = 2.186$, $p < .05$. Collectively, those results show that although less energy was inserted in the NV condition (smaller tangential and radial amplitudes and more loss or less gain in those amplitudes), larger final swing excursions were attained. That seemingly paradoxical result in terms of energy insertion can be understood from the small shifts in phasing (between the CM movements and the swing's motion as well as between the trunk and the lower legs) as observed in the BF condition, accompanied with increased rigidity. Those findings illustrate that it is not the effort per se but the attunement (timing) of the effort to the task that pays off.

Effects of Additional Task Constraints

The difference in PCA34 between the AC condition (96.65%) and the NV condition (96.91%) tended toward significance, $t(17) = -2.041$, $p = .057$. Given that PCA12

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

was not affected, that tendency suggested that in the AC condition the higher PCA modes had gained in importance. That notion was confirmed by the observed significant difference in PCA56 between the AC condition (2.72%) and the NV condition (2.34%), $t(17) = 2.642$, $p < .05$, which reflected the changes in activity required to comply with the additional task constraint. The difference in trunk–leg coupling $\rho(\alpha,\beta)$ also tended toward significance: The values were lower in the AC condition (0.951) than in the NV condition (0.956), $t(17) = -1.948$, $p = .068$. That finding implies that the trunk–leg coordination was not geared solely to amplitude increase but also played a role in the attunement to the visual environment, which is consistent with the other findings reported in this paragraph.

The amplitude reached at the end of the trial, ϕ_{max}, was significantly smaller in the AC condition than in the NV condition (60.7° and 65.2°, respectively), $t(17) = -3.667$, $p < .005$. The change in tangential amplitude V_{tan} was smaller in the AC condition (–0.0016 m/s) than in the NV condition (–0.0026 m/s), $t(17) = 3.233$, $p < .005$. In other words, the contribution of tangential energy insertion decreased more strongly during normal swinging than during swinging with additional task constraints. Because the maximal amplitude was smaller in the AC condition, one can conclude that the process of energy insertion was less effective in that condition.

Effects of Optical Flow Enhancement Versus Reduction

The variability of φ (s_0) provides an appropriate measure for the quality of task performance in the OFE and the OFR conditions, because it is directly related to the phasing requirement. However, the difference between the OFR condition (.1980) and the OFE condition (.1836) was not significant, $t(17) = 1.464$, $p = .161$. Thus, the strength of coupling between the swinging action and the visual environment did not differ over the two phasing conditions.

In terms of negotiating the mechanics of the task, however, the system was not indifferent to the phasing requirements. The change in V_{tan} was significantly greater during the OFR trials (–.0021 m/s) than during the OFE trials (–.0010 m/s), $t(17) = -2.184$, $p < .05$. In other words, the contribution of tangential energy insertion decreased more strongly during OFR than during OFE oscillation. The mean OFR value of V_{tan} corresponded closely to the value found in the NV condition (–.0026 m/s). The measure of harmonicity $H(\theta)$ was also affected by the phasing requirements (OFR = .9664; OFE = .9603), $t(17) = 2.457$, $p < .05$. Because $H(\theta)$ reflects the smoothness of performance, that finding suggests that the coordination requirements in the OFR condition were easier to meet. The phasing between the tangential movement of the CM and the swing rotation $\tau(CM_{tan},\phi)$ was significantly more advanced in the OFE condition (109°) than in the OFR condition (103°), $t(17) = -2.167$, $p < .05$. A similar phasing difference was observed between the trunk and the lower leg: $\tau(\alpha,\beta)$ was more advanced in the OFE condition (19°) than in the OFR condition (16°), $t(17) = -2.968$, $p < .01$. For both $\tau(CM_{tan},\phi)$ and $\tau(\alpha,\beta)$, the phase leads obtained for the OFR condition were similar to those obtained for unconstrained, normal swinging.

Discussion

In the present study, changes in the coordinative structure of swinging induced by withdrawal of visual information as well as by the introduction of specific phasing requirements with regard to a moving display were examined. In addition, the experimental manipulations allowed us to gain preliminary insights into the type of information that is used in the coordination of playground swinging.

As argued before, a swinger is severely constrained by the mechanical properties of the swing–swinger system. Nevertheless, the fact that the participants in the present experiment were able to adapt to the various experimental manipulations proved in a very general sense that there still was room left for flexibility and adaptation, albeit little. Notwithstanding the limitations imposed on the swinger by the mechanics of the task, subtle yet noticeable changes in the coordination characteristics occurred. In the following, those changes in coordination are summarized and discussed in the context of the three research questions that motivated this study.

The Influence of Visual Information

In the present experiment, the most severe manipulation of the available visual information was that we removed it by blindfolding the participant. Because perceptual information usually plays an important role in the guidance of complex movements, we expected that removing the visual information would affect the swinging behavior considerably. That expectation was confirmed with reference to the style of energy insertion: All CM amplitude variables indicated enhanced effort in the BF condition as compared with the NV condition. Regarding the first six principal components, the first and second modes as well as the fifth and sixth modes became less important, whereas the third and fourth modes became more important in the BF condition. That finding implies that the activity of the swinger was characterized by a more stereotyped (counter)rotation of the trunk and lower legs. At the level of coordination between different parts of the body (trunk and lower leg), cross-correlations were significantly higher in the BF than in the NV condition. One can conclude that the trunk and lower leg were more strongly coupled when visual information was not available, resulting in less efficient energy insertion into the swing (viz. increased energy insertion but decreased swinging amplitude).[2]

An explanation of those findings can be found in the theoretical ideas of Bernstein (1967), who conceptualized skill acquisition as a process of mastering redundant degrees of freedom. In learning experiments on drawing (van Emmerik, 1992), throwing (McDonald, van Emmerik, & Newell, 1989), and slalom-like skiing movements (Vereijken, Whiting, & Beek, 1992), it was shown that early in practice, relative joint movements were highly correlated, whereas later in practice, correlations between joint angles decreased and

limb movements became more independent: the so-called freezing and freeing of degrees of freedom. Following Bernstein, skill improvement seems to be characterized by a gradual release of the rigid control of the various degrees of freedom. The present findings with regard to the cross-correlation measures provided support for drawing a parallel between those learning experiments and the swinging task studied here. All participants were experienced swingers, but only in a natural setting. Assuming that they did not learn to swing blindfolded in childhood, removing visual information affected swinging in such a way that swingers had to "freeze out" mechanical degrees of freedom to produce a dynamic, controllable coordinative structure. The observed changes in intersegmental coordination supported our expectation that the absence of visual information would result in more stereotyped performance. It is important to notice, however, that in the learning experiments mentioned earlier, cross-correlations varied from .2 to .5 in the well-practiced state to .8 to .9 earlier in practice. In the experiment reported here, cross-correlations were, for both the BF and the NV conditions, higher than .9. That finding can be explained by the mechanical constraints of swinging: If body segments do not move in synergy, pumping the swing to greater amplitudes becomes impossible.

The Influence of Additional Task Constraints

Subjecting the swinger to an additional constraint in the form of a specific phasing requirement with regard to a moving display resulted in a decrease of the finally reached maximal amplitude of the swing accompanied by a decrease of the importance of the third and fourth PCA modes (PCA34). The increased importance of the subsequent two dimensions (PCA56) is reminiscent of the finding of Post et al. (2000) that increasing task demands (in that experiment, juggling at a high frequency) lead to an increase in dimensionality of the system. Moreover, the cross-correlation between trunk and leg movements tended to be lower in the more constrained conditions. That finding can be understood from the fact that the added relative phasing constraint required phase adaptations from the swinger. Those were brought about by the only means available to the swinger, that is, rotations of body segments. The regularity in those rotations was partially sacrificed (reducing PCA34, increasing PCA56) to the benefit of optimal alignment with the stimulus. Invariably, the alignment occurred in the first part of the trial, that is, at small amplitudes. A slightly reduced coupling between the trunk and the legs, resulting in reduced final amplitude, attested to the cost of serving two incongruent constraints.

The Influence of the Direction of Flow Field Oscillation

Three expectations were formulated with regard to OFE swinging (moving forward while the manipulated optical flow field diverged, resulting in enhanced optical flow) and OFR swinging (moving forward while the manipulated optical flow field converged, resulting in reduced optical flow). On the basis of the theoretical assumptions outlined in the introduction, we expected different effects with regard to swinging amplitude (Expectation A: a larger amplitude for OFR than for OFE) or to the performance characteristics in general, with either OFR (Expectation B) or OFE (cf. Expectation C) leading to smoother and more effective behavior.

The OFE and OFR conditions did not differ with regard to the maximally reached swinging amplitude, a finding that is counter to Expectation A. Subtle changes were observed in variables that pertain to the interlimb coordination of the actor. In comparison with the OFR condition, a slower decrease of tangential amplitude and a lower harmonicity score were observed in the OFE swinging condition. More important, the two conditions resulted in different phasing relations between the tangential movements and the swing, and between trunk and lower legs. Because the results for the OFR condition strongly resembled those obtained for the normal condition, those findings indicate that energy insertion was less effective in the OFE swinging condition. That leads us to the conclusion that, from a coordination perspective, performance was better in the OFR condition, which may indicate that, in accordance with Expectation B, the participants preferred to reduce the optical flow, thereby approaching the normal situation (i.e., nonoscillating visual environment). (Note that even in the OFR condition, the magnitude of the optical flow was larger than that experienced in normal swinging.) Moreover, those results indicate that the mismatch in perceived direction of motion (present in the OFR condition) did not hamper performance. As such, the assumption underlying Expectation C was not corroborated.

It is interesting to note that no significant differences were found between the OFE and OFR conditions regarding the relative phase variability, whereas changes in the swing–swinger system did occur (both CM–swing phasing and trunk–leg phasing were affected). Those findings might suggest that intersegmental coordination constitutes a different level of organization than the coupling between actor and environment. Such an interpretation raises the question of to what extent changes at one level (intersegmental coordination) are independent from changes at another level (actor–environment coupling; cf. Schöner, 1995). In the present context, the phasing task requirements were accommodated by means of continuous adaptations, which manifested themselves as small corrective movements confined to the level of intersegmental coordination.

General Conclusion

It has been argued that the human action system is capable of transforming itself into task-specific devices (Bingham, 1988), that is, perceptual-motor organizations that are effectively and adaptively geared toward achieving specific task goals. In the present study, we focused on the adaptability of such coordinative structures. We demonstrated that even in the presence of severe mechanical constraints, such as are encountered in playground swinging,

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012

adaptability is still noticeable. That finding underscores the resourcefulness of the human action system. However, we had to use sensitive methods such as principal components analysis to uncover the subtle changes that reflected that flexibility.

ACKNOWLEDGMENTS

The authors thank Esther Prins and Renske van Weperen for their help in this project, and Bert Coolen and Bert Clairbois for their technical assistance. The RESPO company (Vroomshoop, The Netherlands) is gratefully acknowledged for the donation of the playground swing. A fellowship of the Royal Netherlands Academy of Arts and Sciences made possible the contribution of C. E. (Lieke) Peper.

NOTES

1. Because the terms *parametric pumping* and *driven oscillation*, as introduced by Case (1996; Case & Swanson, 1990), are not unproblematic (cf. Post, 2001), we prefer the terms *radial movement* and *tangential movement* of the CM.

2. Note that the CM amplitudes in both the radial and tangential directions were larger in the BF condition (cf. Table 1), implying increased excursions of the trunk and lower legs. That finding indicates that the participants were not afraid to make the necessary pumping movements while blindfolded. As such, it seems unlikely that the decreased swinging amplitude simply resulted from fear of swinging in the BF condition.

REFERENCES

Alexandrov, A., Frolov, A., & Massion, J. (1998). Axial synergies during human upper trunk bending. *Experimental Brain Research, 118,* 210–220.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements.* Oxford, England: Pergamon Press.

Bingham, G. P. (1988). Task-specific devices and the perceptual bottleneck. *Human Movement Science, 7,* 225–264.

Case, W. B. (1996). The pumping of a swing from the standing position. *American Journal of Physics, 64,* 215–220.

Case, W. B., & Swanson, M. A. (1990). The pumping of a swing from the seated position. *American Journal of Physics, 58,* 463–467.

Dijkstra, T. M., Schöner, G., Giese, M. A., & Gielen, C. C. (1994). Frequency dependence of the action-perception cycle for postural control in a moving visual environment: Relative phase dynamics. *Biological Cybernetics, 71,* 489–501.

Goldfield, E. C., Kay, B. A., & Warren, W. H. (1993). Infants bouncing: The assembly and tuniing of actions systems. *Child Development, 64,* 1128–1142.

Gore, B. F. (1970). The child's swing. *American Journal of Physics, 38,* 378–379.

Haken, H. (1996). *Principles of brain functioning: A synergetic approach to brain activity, behavior and cognition.* Berlin: Springer Verlag.

Jaric, S., Ferreira, S. M. S., Tortoza, C., Marconi, N. F., & Almeida, G. L. (1999). Effects of displacement and trajectory length on the variability pattern of reaching movements. *Journal of Motor Behavior, 31,* 303–308.

Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.). Upper Saddle River, NJ: Prentice-Hall.

Kugler, P. N., Kelso, J. A. S., & Turvey, M. T. (1980). On the concept of coordinative structures as dissipative structures: I. Theoretical lines of convergence. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 3–47). Amsterdam: North-Holland.

Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law and the self-assembly of rhythmic movement.* Hillsdale, NJ: Erlbaum.

Mah, C. D., Hulliger, M., Lee, R. G., & O'Callaghan, I. S. (1994). Quantitative analysis of human movement synergies: Constructive pattern analysis for gait. *Journal of Motor Behavior, 26,* 83–102.

Mardia, K. V. (1972). *Statistics of directional data.* London: Academic Press.

McDonald, P. V., van Emmerik, R. E. A., & Newell, K. M. (1989). The effects of practice on limb kinematics in a throwing task. *Journal of Motor Behavior, 21,* 245–264.

Peper, C. E., Beek, P. J., & van Wieringen, P. C. W. (1995). Coupling strength in tapping a 2:3 polyrhythm. *Human Movement Science, 14,* 217–245.

Pigeon, P., Yahia, L., Mitnitski, A. B., & Feldman, A. G. (2000). Superposition of independent units of coordination during pointing movements involving the trunk with and without visual feedback. *Experimental Brain Research, 131,* 336–349.

Plagenhoef, S., Evans, G. E., & Abdelnour, T. (1983). Anatomical data for analyzing human motion. *Research Quarterly for Exercise and Sport, 54,* 169–178.

Post, A. A. (2001). *Effects of task constraints on the relative phasing of rhythmic movements.* (Doctoral dissertation). Enschede, The Netherlands: Ipskamp.

Post, A. A., Daffertshofer, A., & Beek, P. J. (2000). Principal component analysis in three-ball cascade juggling. *Biological Cybernetics, 82,* 143–152.

Schöner, G. (1995). Recent developments and problems in human movement science and their conceptual implications. *Ecological Psychology, 7,* 291–314.

Tea, P. L., & Falk, H. (1968). Pumping on a swing. *American Journal of Physics, 36,* 1165–1166.

van Emmerik, R. E. A. (1992). Kinematic adaptations to perturbations as a function of practice in rhythmic drawing movements. *Journal of Motor Behavior, 24,* 117–131.

Vereijken, B., Whiting, H. T., & Beek, W. J. (1992). A dynamical systems approach to skill acquisition. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology, 45A,* 323–344.

Vernazza-Martin, S., Martin, N., & Massion, J. (1999). Kinematic synergies and equilibrium control during trunk movement under loaded and unloaded conditions. *Experimental Brain Research, 128,* 517–526.

Walker, J. (1989). How to get the playground swing going: A first lesson in the mechanics of rotation. *Scientific American, 260,* 86–89.

Submitted September 7, 2000
Revised February 15, 2002

Downloaded by [Vrije Universiteit Amsterdam] at 05:32 26 October 2012